# REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188



| 1. REPORT DATE (DD-MM-YYYY) | 2. REPORT TYPE | 3. DATES COVERED (From - To) |
|---|---|---|
| 02-09-2010 | Final Report | 15-May-2007 - 14-May-2010 |

4. TITLE AND SUBTITLE
Ultra-Wideband Impulse Radio for Tactical Ad-Hoc Military Communications: Final Report

5a. CONTRACT NUMBER
W911NF-07-1-0275

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

6. AUTHORS
J. Keith Townsend, Liping Li

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
North Carolina State University
Office of Contract and Grants
Leazar Hall Lower Level- MC
Raleigh, NC 27695 -7214

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
52599-CS.1

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
The simple ultra-wideband (UWB) communications receiver structure is especially attractive to applications which require low cost and low power consumption. However, the envisioned simple receiver designs are also fraught with challenges Transmitted Reference (TR) UWB systems have been proposed in the literature as one way to avoid channel estimation while still maintaining a relatively simple receiver structure. In this project, we investigated the performance of TR UWB communication systems in multiple-access environments. We remove

15. SUBJECT TERMS
UWB, Ultra-Wideband, Impulse Radio, synchronization, near-far problem

| 16. SECURITY CLASSIFICATION OF: a. REPORT | b. ABSTRACT | c. THIS PAGE | 17. LIMITATION OF ABSTRACT | 15. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| UU | UU | UU | UU | | J. Townsend |
| | | | | | 19b. TELEPHONE NUMBER |
| | | | | | 919-515-2444 |

## Report Title

Ultra-Wideband Impulse Radio for Tactical Ad-Hoc Military Communications: Final Report

## ABSTRACT

The simple ultra-wideband (UWB) communications receiver structure is especially attractive to applications which require low cost and low power consumption. However, the envisioned simple receiver designs are also fraught with challenges Transmitted Reference (TR) UWB systems have been proposed in the literature as one way to avoid channel estimation while still maintaining a relatively simple receiver structure. In this project, we investigated the performance of TR UWB communication systems in multiple-access environments. We remove the commonly invoked assumption of perfect power control. We investigate the multiple access interference (MAI) of TR UWB systems, as well as frequency-shifted reference (FSR) UWB systems. In this project, we propose and investigate a synchronization procedure which is near-far resistant. By exploiting the structure of interfering power levels, we devise an efficient suppression technique which only requires the knowledge of the spreading code of the desired user. Complex matrix operations required by other techniques found in the CDMA literature are not required in our suppression process. Simulation results validate our proposed near-far resistant synchronization technique and the superior performance is shown when compared to the current literature.

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## List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

### (a) Papers published in peer-reviewed journals (N/A for none)

L. Li, J. K. Townsend, "M-ary PPM for Transmitted Reference Ultra-Wideband Communications", IEEE Trans. on Commun., Vol 58, No. 7, July, 2010, pp. 1912-1917.

**Number of Papers published in peer-reviewed journals:** 1.00

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### (b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

**Number of Papers published in non peer-reviewed journals:** 0.00

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### (c) Presentations

**Number of Presentations:** 0.00

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### Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

**Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):** 0

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### Peer-Reviewed Conference Proceeding publications (other than abstracts):

L. Li, J. K. Townsend, R. J. Ulman, "Performance of Transmitted Reference UWB Communications with Imperfect Power Control", in Proceedings of MILCOM 2007.

L. Li, J. K. Townsend, R. J. Ulman, "Multiple-Access Performance of Transmitted Reference UWB Communications with M-ary PPM, In proceedings of IEEE Globecom 2008.

L. Li, J. K. Townsend, R. J. Ulman, "Transmitted Reference Ultra-Wideband Communications with M-ary PPM", In proceedings of IEEE Globecom 2008.

L. Li, J. K. Townsend, "Multiple-Access Performance of Slightly Frequency-Shifted Reference UWB", in Proceedings of Milcom 2008.

**Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):** 4

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### (d) Manuscripts

L. Li, J. K. Townsend, "Near-Far Resistant Synchronization for UWB Communications", submitted to IEEE Transactions on Wireless Communications, Nov. 2009.

**Number of Manuscripts:** 1.00

## Patents Submitted

## Patents Awarded

## Graduate Students

| NAME | PERCENT_SUPPORTED |
| --- | --- |
| Liping Li | 1.00 |
| **FTE Equivalent:** | **1.00** |
| **Total Number:** | **1** |

## Names of Post Doctorates

| NAME | PERCENT_SUPPORTED |
| --- | --- |
| **FTE Equivalent:** | |
| **Total Number:** | |

## Names of Faculty Supported

| NAME | PERCENT_SUPPORTED | National Academy Member |
| --- | --- | --- |
| J. Keith Townsend | 0.01 | No |
| **FTE Equivalent:** | **0.01** | |
| **Total Number:** | **1** | |

## Names of Under Graduate students supported

| NAME | PERCENT_SUPPORTED |
| --- | --- |
| **FTE Equivalent:** | |
| **Total Number:** | |

## Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

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The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

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Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense ...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

## Names of Personnel receiving masters degrees

NAME

**Total Number:**

## Names of personnel receiving PHDs

| NAME | |
|---|---|
| Liping Li | |
| **Total Number:** | 1 |

## Names of other research staff

| NAME | PERCENT_SUPPORTED |
|---|---|
| **FTE Equivalent:** | |
| **Total Number:** | |

## Sub Contractors (DD882)

## Inventions (DD882)

# Ultra-Wideband Impulse Radio for Tactical Ad-Hoc Military Communications: Final Report

Funding Agency: U. S. Army Research Office
Contract Number: W911NF-07-1-0275

September 2, 2010

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## I. Summary of Technical Results

Ultra Wideband (UWB) communications systems received a renewed attention in 2002 when Federal Communications Commission (FCC) allocated the 3.1 – 10.6 GHz band for its usage [1]. The allowed power emission level for UWB wireless communications in [1] is extremely low (at the thermal noise level), which enables the coexistence of UWB systems with the legacy systems such as the Global Positioning System (GPS) and IEEE 802.11 wireless local area networks (WLANs). One type of UWB systems, known as impulse radio (IR), results in a very simple receiver structure where intermediate frequency (IF) processing is not required. This feature gives UWB systems an advantage in low-cost receiver designs. The low-power spectral density, low-cost features make UWB systems suitable in applications such as real-time, high-data-rate home entertainment systems, sensor networks, and systems that can exploit the geolocation capability of UWB.

Despite the envisioned advantages, UWB systems are also fraught with implementation challenges. Impulse radio UWB uses narrow pulses on the order of sub-nanoseconds duration, modulated either in time or in amplitude. In a multipath environment, hundreds or thousands of echos of the narrow pulses can be resolved by the receiver. This results in a large diversity gain which can be exploited to improve the performance. It is shown that over fifty fingers in a Rake receiver are required to achieve a satisfactory performance [2]. The complexity in implementing a large number of Rake fingers and the computationally intensive estimation of the channel (required by a Rake receiver) have inspired alternative approaches such as transmitted reference (TR) signaling [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], a scheme which dates back to the 60s [16].

In this project, we have investigated the multiple access issues for TR UWB systems in multipath environments. Networks under consideration included both a large number of active interfering users that have power levels similar to or lower than the desired user, and a small number of users with much higher power levels than the desired user. We differentiate these two types of interference as: interference from equal-power users (the conventional multiple-access interference, MAI) and interference from high-power users. Therefore, the near-far effects are included in the analysis. We have also investigated how the near-far problem affects synchronization for for UWB systems. In this final report we hightlight the results of our investigations, the details of which are give in the following papers: [17], [18], [19], [20], [21], [22], [23].

## II. TRANSMITTED REFERENCE UWB SYSTEMS

In TR UWB systems, signaling is carried out by transmitting a reference pulse before each data-bearing pulse separated by a time interval less than the coherence time of the channel. In contrast, conventional UWB systems transmit one pulse in each frame. Typically multiple pulse/pulse pairs are transmitted per symbol.

The separation of the two pulses, $T_d$, is set to be less than the coherence time of the channel so that the reference pulse and the data-bearing pulse are affected by approximately the same channel conditions. The main advantage of TR systems over UWB systems with Rake receivers is that TR systems do no require channel estimation, while Rake receivers require channel estimation for each finger. By using a delay line, the reference signal is aligned with the data-bearing signal and the correlation is computed between these two signals. The reference signal serves as a template to demodulate the data-bearing signal and a large diversity gain is achieved in this way. The advantage of TR systems also comes from the more relaxed synchronization requirements [24], [25], [26] compared to UWB systems with Rake receivers [27], [28], [29].

TR systems, as any other systems, have disadvantages. One disadvantage is that the reference pulses do not convey information, thus resulting in a 3 dB energy penalty when compared to conventional UWB systems. The reference signal of TR systems is noisy since it is corrupted by at least the additive white Gaussian noise (AWGN). Just as differentially modulated systems, the noise power doubles for TR systems at high SNR. Another disadvantage of TR systems is the difficulty in implementing the analog delay line used to align the reference signal and the data-bearing signal. This difficulty is somewhat resolved by another signaling scheme, frequency-shifted reference (FSR) UWB systems which do not require analog delay lines at the receiver. In this project we investigate the performance of FSR systems relative to TR UWB systems [20], [23].

## III. MULTIPLE ACCESS INTERFERENCE IN TR UWB SYSTEMS

Performance of single-link TR UWB systems is studied in [4], [5], [6], [7], [8], [9], [10], [11], [12]. Multiple-access (MA) performance of TR UWB systems is investigated in [13], [14], and [15]. In these papers, all active users in the network are assumed to have power levels equal to the desired user at the receiver side and their interference is assumed to be Gaussian distributed. The assumption that all users have the same power levels as the desired user frequently does not hold in ad-hoc wireless communications where centralized power control is not employed due to survivability and complexity constraints. In this project, we consider UWB networks where transmitters in close proximity (“high-power”) to a receiver cause significant interference with the desired signal due to the much larger power levels of these signals. We also include a large number of active interfering users that have power levels similar to or lower than the desired user. Performance is quantified under the combined effect of equal-power and high-power users.

### A. High-power Users

In networks without power control, the received power levels from interfering users can vary over many 10's of dB. But this group of high-power users is not included in the MA analysis in the current literature [13], [14], [15]. In this project, we consider the more general situation where the users with much higher power levels than the desired user are included in the analysis. The authors of [14] concluded that the optimal transmission strategy is to concentrate the transmission power in one frame for TR UWB systems. In the presence of high-power users, traditional MA suppression techniques such as in [15] do not guarantee satisfactory performance. Chip discrimination, proposed in [30], [31] for AWGN channels and studied in [32] with multipath channels, is applied in this project to achieve satisfactory performance even in environments exhibiting the so called near-far problem. Our investigation in [17], [23] suggests that for TR UWB systems using binary PAM, the optimal transmission strategy differs from that in [14] which only included equal-power users, and we show how the optimal transmission strategy depending on the system parameters.

The constraint on TR UWB systems to have a large spacing between pulses plus the requirement of chip discrimination to have a low duty cycle results in a low data rate for TR systems. Although the data rate can be increased for TR systems by decreasing the separation time between pulses [15], the data rate is at least somewhat dependent on the delay spread of the channel. In this project, we also investigate one technique, M-ary PPM, to improve the data rate for TR UWB systems in the presence of high-power users. Impulse radio using M-ary PPM has been investigated in a number of settings for UWB systems with Rake receivers [33], [34], [35], [36]. The current literature for TR UWB systems focuses on binary modulation schemes [14], [15]. Performance of the synchronization function of the receiver is investigated for M-ary TR systems in [37]. Our results in the study of high-power interference are published in [19], [23].

### B. Equal-power Users

*1) TR UWB Systems:* The work on multiple-access performance of binary TR UWB systems can be found in [13], [14], [15]. In these papers, all active users in the network are assumed to have equal power at the receiver and their interference is assumed to be Gaussian distributed. The Gaussian assumption for interference from equal-power users for UWB systems with a Rake receiver is used in the literature, for example, [38], [33], and is evaluated in [39], [34], [40], [41], [42], [43]. For a binary TR UWB system, simulation is used to validate this Gaussian assumption of the interference from equal-power users in [14]. The noisy template and the typically longer integration time of the receiver in TR UWB systems makes the Gaussian assumption for MAI more accurate when compared to UWB systems with Rake receivers.

In this project, we have used the Gaussian assumption to model the effect of equal-power users and focus on providing a theoretically tractable performance evaluation for TR UWB systems with M-ary PPM. [19], [18], [21], [23]. Rather than using simulations to show the bit-error-probability (BEP) performance with MAI as found in [14] and [15], we incorporate the power delay profile (PDP) of the channel, inspired by the work in [13], to derive the variance of the MAI, enabling theoretical BEP analysis. Our analysis reveals a general relationship between the variance of the MAI, the shape of the transmitted pulse, and the PDP of the channel. By applying an upper bound on the BEP, the number of equal-power users that the system can support is evaluated for different modulation order $M$. The network throughput in terms of the total bit rate is obtained based on the number of supported equal-power users. Tradeoffs between the system performance and complexity in implementing high-order modulation schemes are investigated. This theoretical contribution can also be used to address two fundamental issues of communications for TR UWB systems using M-ary PPM: 1) To determine the achievable data rate as a function of system resources. 2) To determine the required $E_b/N_0$ for the system to achieve a given BEP.

In this project, the combined effects of both equal-power and high-power users are quantified, including the limit in the data rate in the presence of high-power users, and the optimization of the system performance by finding the optimal operational parameters [19], [18], [21], [23].

*2) FSR UWB Systems:* As discussed earlier, TR UWB systems have been proposed to alleviate the implementation issues of UWB Rake receivers due to channel estimation and the need for a large number of Rake fingers. However, the wideband analog delay line used in TR receivers is difficult to implement in practice as well. A slightly frequency-shifted reference (FSR) UWB system has been introduced in [44] to retain the benefits of TR UWB systems while avoiding the analog delay line of TR systems. The single-link performance of FSR systems has been investigated in [44]. A lightly loaded system with a few users is considered in [45] where the number of users is constrained by the coherence bandwidth of the channel. In this project, we consider general networks with no constraints on the number of users and the MA performance of FSR UWB systems is derived under both AWGN and multipath channel conditions.

The theoretical tool developed for obtaining the MA performance of TR systems is used for FSR systems: the power delay profile (PDP) of the multipath channel is incorporated in the analysis of the MA interference power. A theoretical comparison between FSR and TR UWB systems in a multiuser environment is developed in this project which contributes to the current literature on FSR ultra-wideband systems [20], [23].

## IV. Near-Far Resistant Synchronization

In the UWB literature, narrow-band, single-tone interference is considered in [46], [47], [48] and reference therein, where techniques are investigated to suppress the narrow-band interference. Synchronization for UWB systems in the presence of wide-band multiple access interference (MAI) is studied in [49], [50], [51], [52], [53], [54]. All interfering users in these works are assumed to have power levels lower than or similar to the desired user. The works in [49], [53], [54] are based on the maximal likelihood (ML) criterion for achieving acquisition in multiple-access (MA) environments. The authors in [50], [51] investigate the search orders of the divided bins in the time domain while a frequency-domain procedure for synchronization is studied in [52].

In the CDMA literature, near-far resistant synchronization is studied in [55] where the code waveforms of all users are assumed to be known by the receiver and the complexity is generally high since a global maximization is performed upon all users. In [56], blind synchronization is carried out for users with equal power levels without the knowledge of the codes from all users. Synchronization in a near-far environment which only requires knowledge of the desired user's code is investigated in [57] and [58]. However either the subspace method in [57] or the ML procedure in [58] involves matrix operations (inversions, for example) which makes the methodologies too computationally intensive for UWB communications.

In this project, we investigate the coarse (symbol level) synchronization in environments where there is no power control for UWB communication networks. The power levels from interfering users at the desired receiver can vary over many tens of dB. In this project, we propose and investigate an easy to implement procedure suppress the high-power interfering signals, that does not require knowledge of the interfering users' codes. This procedure uses the fact that the signs of cross correlations between received symbols are determined by dominant signal waveforms from high-power interfering users. Using the knowledge of signs of cross correlations plus the knowledge of the desired user's spreading code, the procedure retains symbols for subsequent processing only when high-power interfering waveforms are combined destructively. Due to the so-called edge effect, we find that the signals from high-power interfering users can not be completely canceled. However the dimension of interfering signals after the suppression procedure is considerably reduced.

We also propose a new dimension-based estimation technique to estimate the code phase from the suppressed signal. The issue of threshold setting is discussed for implementing the dimension detection technique. The suppression procedure and the subsequent dimension detection has low complexity compared with methods in [57] and [58] and requires no additional resources for synchronization than traditional UWB receivers.

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